TASL: A Traffic-Adapted Sleep/Listening MAC Protocol for Wireless Sensor Network

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Abstract: In this paper, we proposed TASL-MAC, a medium-access control (MAC) protocol for wireless sensor networks. In wireless sensor networks, sensor nodes are usually deployed in a special environment, are assigned with long-term work, and are supported by a limited battery. As such, reducing the energy consumption becomes the primary concern with regard to wireless sensor networks. At the same time, reducing the latency in multi-hop data transmission is also very important. In the existing research, sensor nodes are expected to be switched to the sleep mode in order to reduce energy consumption. However, the existing proposals tended to assign the sensors with a fixed Sleep/Listening schedule, which causes unnecessary idle listening problems and conspicuous transmission latency due to the diversity of the traffic-load in the network. TASL-MAC is designed to dynamically adjust the duty listening time based on traffic load. This protocol enables the node with a proper data transfer rate to satisfy the application's requirements. Meanwhile, it can lead to much greater power efficiency by prolonging the nodes' sleeping time when the traffic load of the network decreases. We evaluate our implementation of TASL-MAC in NS-2. The evaluation result indicates that our proposal could explicitly reduce packet delivery latency, and that it could also significantly prolong the lifetime of the entire network when traffic is low.

Key words: Wireless Sensor Network, MAC protocol, traffic aware, sleep/wake mechanism

1. Introduction

We study the problem of media access control (MAC) protocol in the novel regime of sensor networks, where unique application behavior and tight constraints in computation power, storage, energy resources, and multi-hop transition require this design space to be very different from traditional wireless networks.

Although many of the high level architectural and programming aspects in this area are still being resolved, the underlying media access control and transmission control protocols are critical enabling technology for many sensor network applications.

The application behavior in sensor networks leads to very different traffic characteristics from those found in conventional computer networks. A wireless sensor network is a collection of sensor nodes that is spread around an area in which a certain phenomenon of interest is expected to take place. For example, in a general wireless sensor network scenario, when an abnormal event such as a fire is detected, all the sensors which detected the object will send the collected data to the base station by multi-hop connection.

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According to the constraints of data transmission in wireless sensor networks as mentioned above, a well-designed MAC protocol should achieve the following three requirements:

Requirement 1: Energy efficiency

The first requirement concerns energy efficiency. Sensor nodes are likely to be battery operated, and are generally assigned long-term works. Therefore, power efficiency is the primary consideration in designing an MAC protocol for wireless sensor networks.

Requirement 2: Reduction of transmission latency

Multitudinous applications are usually constrained by strict time limitations, so collected data from the sensor nodes in the networks which adopt such applications should be transferred in time. Overtime data is meaningless for these kinds of applications. Therefore, it is also very important to reduce the data transmission latency.

Requirement 3: Scalability and adaptability

Other important attributes are scalability and adaptability to change. Changes in node density and topology should be handled rapidly and effectively. A good MAC protocol should gracefully adapt the network to such changes.

In the following sections, we will describe related works, our proposed MAC protocol TASL-MAC, and the simulation in Sections 2, 3, and 4, respectively. Finally, we will conclude in Section 5.

2. Related Work

Various MAC protocols have been proposed for wireless sensor networks. Current MAC protocols for sensor networks can be divided into TDMA and contention-based protocols.

The proposed TDMA protocols are based on performing TDMA scheduling in communication clusters. The overhead incurred in forming these clusters and inter-cluster Communication /Interference may eliminate the efficiency of TDMA. Therefore, when adopted into large-scale sensor networks, TDMA may not be able to provide sufficient performance for the network's requirements in terms of scalability and adaptability.

The standardized IEEE 802.11 [4] is an example of the contention-based protocol. It is widely used in wireless ad hoc networks because of its simplicity and robustness with respect to the hidden terminal problem. However, recent work has shown that the energy consumption of this MAC is very high when the nodes are in idle mode. This is mainly due to idle listening.

In order to remit the power consumption of the nodes' idle listening, the protocol in [5], called S-MAC, is proposed. As shown in Fig. 1, S-MAC make nodes periodically listen and sleep, and neighboring nodes form virtual clusters and follow the same sleep schedule. Nodes that reside in two separate virtual clusters are called "border nodes". In order to relay data, border nodes are set to listen when any of the two clusters are in the listening status. The drawback of the S-MAC algorithm is that the border nodes have to follow two schedules, which results in more energy consumption via idle listening and over-hearing. Moreover, when the traffic load is higher than the node's data transmission capability provided by the fixed duty listening time, the S-MAC will inevitably cause transmission latency, especially in the case of multi-hop routing sensor networks, since all immediate nodes have to wait until the next node is woken up for listening. Therefore, S-MAC can achieve requirement 1 to a certain extent, but cannot achieve requirement 2 in a relatively high traffic-load state.

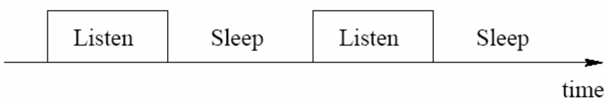

Fig. 1. S-MAC Periodic listening and sleep schedule

To solve the many problems which are led by the border nodes in S-MAC, Tae-Seok Lee introduced a unifying scheduling mechanism called H-SYNC (Heartbeat-SYNC) [6] to synchronize all the sensor nodes' Sleep/Listening time rate with the base station. This mechanism is able to eliminate the "border nodes" in S-MAC. In other words, the mechanism overcomes border node problems by adopting a policy for enabling the whole network to be unified by a single schedule and provides better performance in terms of energy efficiency and the remission of transmission latency than S-MAC. However, like S-MAC, H-SYNC's fixed Sleep/Listening schedule still lacks the capability to deal with the variety of the data traffic load.

3. Proposed Traffic-load Aware MAC Protocol

For the three requirements described in the section 1, our proposed MAC protocol TASL-MAC also follows contention based mechanism to achieve the third requirement. Furthermore, we adopt dynamic adjustment of Sleep/Listening rate of the sensor nodes and a synchronization mechanism to achieve the first requirement and the second requirement. This section describes TASL-MAC in detail.

3.1. Maintain Synchronization

With regard to overcoming the transmission latency problems in virtual clusters in S-MAC, we introduce a new synchronization mechanism. We let a sensor node synchronize to its up level nodes, which are called parent nodes. As Fig. 2 shows, a sensor node is assigned a level value based on its relative position to the base station. For example, as the base station is assigned as the level 0 node, the closest nodes to the base station are assigned as level 1 nodes. After the construction of the level structure of the network, nodes will synchronize with their corresponding parent nodes by periodically broadcasting SYNC packets that are very short, and contain the sender's address and the current scheduling. After the synchronization, the time rates of the senders' neighbor nodes will be synchronized with the senders.

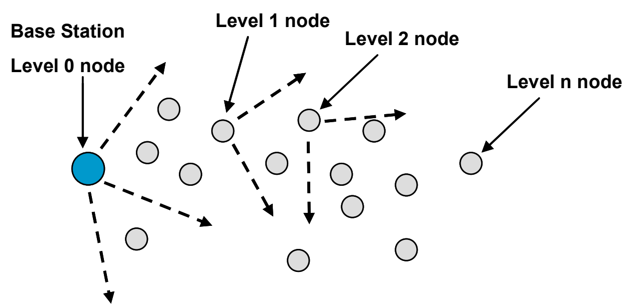

Fig. 2. Parent node

In order to receive SYNC packets, Burst-Info packets, and data packets for a sensor node, we divide its listening interval into three parts. As shown in Fig. 3, the first part is for receiving SYNC packets, the second is for receiving Burst-Info packets, and the third is for data transmission. As shown in Fig. 3, each part is further divided into many time slots in order for the senders to perform the carrier sense. For example, if a sender wants to send an SYNC packet, it starts the carrier sense when the receiver begins listening. It randomly selects a time slot in which to complete its carrier sense. If it has not detected any transmission by the end of the time slot, it wins the medium and starts sending its SYNC packet at that time. The same procedure is followed when sending data packets.

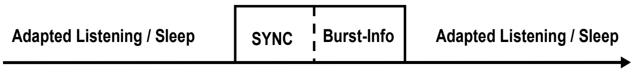

Fig. 3. TASL-MAC time interval assignment

If multiple neighbors want to talk to a node which is in the duty listening state, they need to contend for the medium. The contention mechanism is the same as that in IEEE 802.11, i.e. using RTS (Request To Send) and CTS (Clear To Send) packets. The node that sends out the RTS packet wins the medium at first, and the receiver will reply with a CTS packet. Once the sender receives the CTS packet, it will start the data transmission process with the receiver.

3.2. Duty Listening Time Adjustment

This section introduces the adjustment of the schedule of the sensor nodes' listening and sleep rate.

Because of the unproportionate problem between the bandwidth required in practice and the bandwidth provided by the sensor nodes, the MAC needs to control its duty listening time length to ensure that the data can obtain channel access and reach the base station. Our duty listening time control initially measures the data packet length and then uses a gradual increase and fast decrease approach to adjust the duty listening time. In our protocol, we adopt [8] to detect the data traffic of the network and the data packet length. Firstly, the node uses the maximum duty listening time, and if there is any duty listening time left once the required data transmission is finished, it will reduce the duty listening time in the next cycle rapidly. In the following cycle, if there still remains any duty listening time, it will reduce the listening time again. The process will be repeated until the bandwidth meets the required bandwidth. Otherwise, if all current duty listening time has been utilized but it still cannot satisfy the required data transition, the sensor node will extend the duty listening time.

Furthermore, in order to handle burst data transmission, for example, when a sensor network remaining inactive for long periods suddenly needs to transmit a great deal of data, we add a Burst-Info interval before data transmission, as shown in Fig. 3. In this time interval, if a sensor node has too many data packets to transmit suddenly, then in order to increase the network's data transmission capability, the node will send a Burst-Info packet to the receiver nodes to request for more listening time to receive the data packet. The nodes that receive the Burst-Info packets immediately increase their duty listening time accordingly. A more detailed description has been given in the algorithm 1.

Algorithm 1:

```
Incoming Data Message: Inc_Data
Constant: Max_DutyCycle, r, r_Burst
Local Variables: dutyCycle
System Functions: Predict()
If {the first time to send data} do
   dutyCycle = Max_DutyCycle
     return
end if
if (Inc_Data < dutyCycle) do
   dutyCycle = Inc_Data
   end if
if (Inc_Data > dutyCycle) do
   dutyCycle = dutyCycle + r*dutyCycle
   end if
if (Inc_Data == Burst-info) do
   dutyCycle = dutyCycle + r_Burst*dutyCycle
end if
```

Here r and r_Burst are the increased rates of the duty listening time according to the application scenario. For example, in our simulation, we assume r to be 5% and r_Burst to be 15%. According to our simulation result, these can satisfy most of the application requirements.

The advantage of the dynamic duty listening time adjustment mechanism is that it suited to the diversity of the traffic-load in the wireless sensor networks. It can not only save on energy consumption by avoiding unnecessary idle listening in general low data transmission periods, but can also increase its data transmission capability to meet the requirements to reduce the transmission latency in certain potential special situations.

4. Simulation

We implemented our prototype in the NS-2 network simulator. The node radio characteristics are shown in Table 1. The energy costs of the Tx:Rx:Slp radio modes are 1.78:1:0.06. SMAC and H-SYNC have a basic duty cycle of 50%. This means in a 100ms frame, with a sleep period of 50ms, and 50ms for listening. TASL-MAC follows the same frame length, but the duty listening length is adapted with the traffic load, and the increase rate of the duty listening time r and r_Burst is assigned as 5% and 15% respectively.

Table 1. Node Radio Parameters

Radio bandwidth	20Kbps
Radio Transmission Range	10 m
Packet Length	10bytes
Transmission Power	8.2mA
Receiver Power	4.6mA
Sleep Power	30uA

Fig. 4. Network Topology

4.1. Energy Consumption Comparison

We compare the energy consumption of different MAC protocols with various traffic loads. The energy consumption is measured using the sum of energy consumed by all the sensor nodes on the data transmission routing.

In our experiments we have used a static network with a 10×10 grid topology, as shown in Fig. 4. We have chosen a radio range in which the non-edge nodes all have 8 neighbors. All the source nodes generate data packets and transmit to the base station, which is located in the top left-hand corner of the grid.

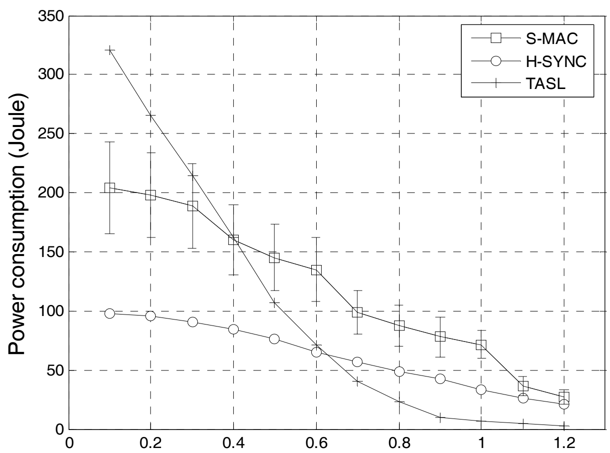

Fig. 5. Energy consumption

From Fig. 5, which shows the energy consumption of the MAC protocols, it may be inferred that, when the data generation interval is less than 0.5 seconds, which signifies comparatively less data traffic, TASL-MAC's energy consumption is conspicuously lower than that of both S-MAC and H-SYNC. The result shows that although S-MAC and H-SYNC could both reduce energy consumption by adopting a sleeping/listening schedule, their idle listening energy consumption is still higher than TASL-MAC when the data transmitted does not exceed the transmission capability of the node. In contrast, the TASL-MAC performs better by creating a traffic aware listening/sleeping time rate for the sensor nodes.

When the interval of data generation of the source nodes decreases, the data transmitted from the source nodes will increase. In this situation, the energy consumption of TASL-MAC will increase accordingly and finally exceed the other two protocols' energy consumption. This is because the duty listening time of S-MAC and H-SYNC is invariable, even if the actual data transmission requirement exceeds the node's capacity. In contrast, in order to reduce the data transmission latency, TASL-MAC will increase the node's duty listening time. Although it brings about a higher level of energy consumption, the transmission latency will be conspicuously reduced.

4.2. Latency Analysis

To measure the latency, we use a similar approach introduced in the section 4.1 of constantly adjusting the interval for the source nodes to send packets and to change the data volume.

Fig. 6 shows the measured mean message latency under different traffic loads. When the traffic load is low, the duty listening time of S-MAC and H-SYNC provides sufficient data relay capability, which can cover the required bandwidth for data transfer.

At this time, the delay of the three methods is similar. The reason for the latency is that each message has to wait for one sleep cycle on each hop.

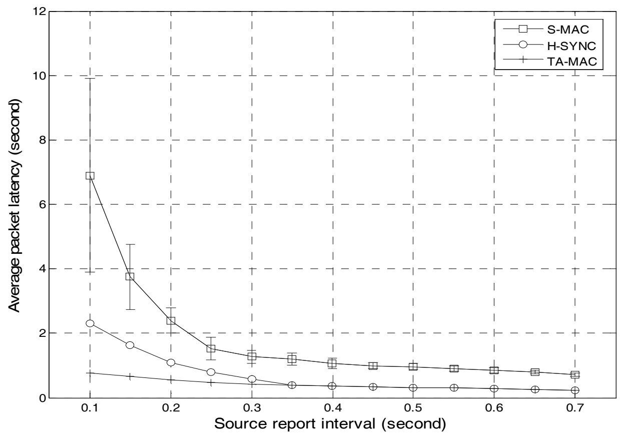

Fig. 6. Average energy consumption

But when the traffic load exceeds that which can be covered by the fixed duty listening cycle of S-MAC and H-SYNC, the latency turns out to be higher than that of TASL-MAC's.

5. Conclusion

In this paper, we focus on minimizing the latency of data transmission along a multi-hop route in the sensor networks. We propose an MAC protocol which can dynamically adjust the listening/sleeping time rate of the wireless sensor nodes according to the data traffic load.

Our simulation results have shown that TA achieves both energy savings and low latency. Our proposed scheme is useful in various delay-sensitive applications and scenarios where sensing data is required within a certain time period.

In our future work, we aim to apply this MAC to a Mote-based [7] sensor network platform and evaluate its performance through real experiments.

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